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Polarization Possibilities of Small Spin-Orbit Interaction in Strained-Superlattice Photocathodes*

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Abstract.

Strained-superlattice photocathodes based on InGaP/GaAs were investigated. The photocathode performance is found highly dependent on the superlattice parameters. The electron confinement energy in superlattice appears important.

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Keywords: polarized electrons, superlattice

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INTRODUCTION

The strained-superlattice structure based on GaAsP/GaAs, with a maximum polarization as high as 90% and more than 1% quantum efficiency, is presently the prime candidate for the ILC polarized electron photocathodes. A recent systematic study shows, however, that the peak polarization seems saturated even though the heavy-hole (HH) and light-hole (LH) band splitting is increased significantly, indicating that there is a material specific spin relaxation mechanism [1]. It is widely accepted that the D'yakonov-Perel mechanism is the dominant spin relaxation mechanism in the III-V compound superlattice structures with a low *p*-doping ($\leq 10^{17}$ cm^{-3}), and that the spin relaxation may be reduced by choosing a material with a smaller spin-orbit interaction. As the spin-orbit interaction in phosphides is much smaller than in arsenides, strained-superlattice structure based on InGaP/GaAs were investigated. The computer code SPECCODE developed by Subashiev and Gerchikov has been used for calculating the band structures in superlattice [2].

STRAIN EFFECT IN GaAsP/GaAs SUPERLATTICE

The lattice-mismatch between the well (GaAs) and the barrier (GaAsP) changes when the phosphorus faction is varied. While a larger phosphorus fraction generates a larger strain and therefore a larger energy splitting between the HH and LH bands, the strain within a layer may relax if the lattice-mismatch becomes too large. The phosphorus fraction was increased from 0.25 to 0.40 keeping the total superlattice thickness constant. Figure 1 shows the peak polarization as a function of the phosphorus fraction. The measured HH-LH energy splitting is also shown in the figure together with the SPECCODE predictions for 100% strained structure. As the phosphorus fraction is increased, the layer begins to relax. But the relaxation does not exceed 16% even at the highest phosphorus fraction of 0.4. Although the HH-LH energy splitting increases from 60 meV to 89 meV, the peak polarization does not change significantly at about 85%, indicating that this degree of energy splitting is sufficient to maximize the spin polarization. A spin-relaxation mechanism specific to the GaAsP/GaAs structure appears to be present.

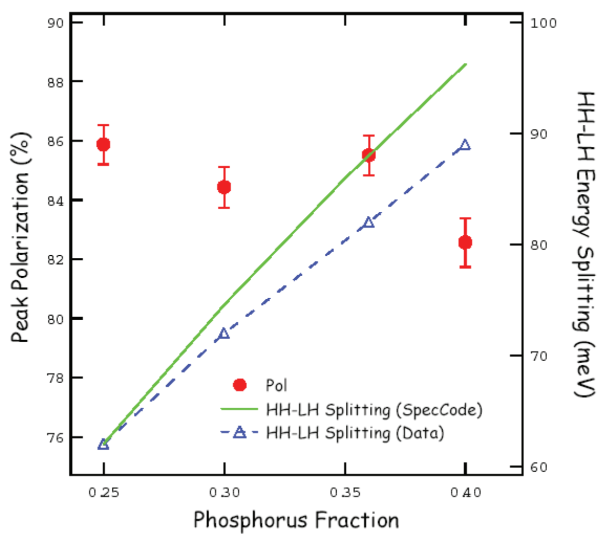

FIGURE 1. Peak polarization (solid circles) and measured HH-LH splitting (triangles) as a function of the phosphorus fraction. The HH-LH splitting calculated by SPECCODE for fully strained structure is shown in solid line.

SPIN-RELAXATION AND InGaP/GaAs SUPERLATTICE

In photoemission from a thin epitaxial layer, the polarization, P, may be expressed by

$$P = P_0 \frac{\tau_s}{\tau_s + < \tau >} P_{BBR} , \tag{1}$$

where P_0 is the initial polarization, τ_s the spin-relaxation time, $<\tau>$ the average photoemission time, and P_{BBR} any additional depolarization generated in the band bending region. The average photoemission time for a 100-nm thick strained GaAs cathode has been measured to be $<\tau>$ ~ 3 ps [3]. A spin-relaxation time shorter than about 50 ps would have a significant effect on polarization. The dominant spin relaxation mechanism in the III-V compound superlattice structures is the D'yakonov-Perel mechanism via the spin-orbit interaction. Therefore, the spin relaxation may be reduced by choosing a material with a smaller spin-orbit interaction. As the spin-orbit interaction in phosphides is much smaller than in arsenides, we have investigated the strained-superlattice structure based on InGaP/GaAs, replacing GaAsP with InGaP.

As $In_{0.48}Ga_{0.52}P$ is lattice-matched to GaAs, it is possible to grow a strained-well superlattice using less than 48% In or a strained-barrier superlattice using more than 48% In. Three different structures have been grown at SVT Associates using gas-source MBE: one strained-well $In_{0.32}Ga_{0.68}P$/GaAs structure and two strained-barrier $In_{0.65}Ga_{0.35}P$/GaAs structures. A lattice-mismatch of 1.25% between GaAs and InGaP is used for both structures. Table I summarizes the sample parameters together with the experimental results on quantum efficiency (QE) at 670 nm and peak polarization.

Table I. Sample parameters and experimental results

	GaAs (nm)	InGaP (nm)	In	Band Gap Energy (eV)	HH-LH Splitting (meV)	ΔE_{1e} (meV)	QE (%) @ 670 nm	Polarization (%)
1	4.0	4.0	0.32	1.57	108	76	0.4	68
2	1.5	4.0	0.65	1.47	94	43	0.002	40
3	4.0	1.5	0.65	1.44	54	17	0.01	68

DISCUSSION

As seen in Table I, the photocathode performance is highly dependent on the superlattice parameters. Sample 1, the strained-well structure, yielded 68% polarization, while the $GaAs_{0.64}P_{0.36}$/GaAs structure with the same superlattice parameters shows 86% as seen in Figure 1. In particular, the two strained-barrier samples yielded very different QE and polarization. While Sample 2 was expected to have a higher polarization than Sample 3 because of the larger HH-LH splitting, the experimental result was opposite, indicating that the superlattice parameters (well and barrier thickness) are more important than having a large HH-LH energy splitting.

Spin relaxation near room temperature is dominated by a spin precession mechanism in an internal crystal magnetic field, the D'yakonov-Perel mechanism. The spin relaxation rate depends on the effective magnetic field, which results from the lack of crystal inversion symmetry and the spin-orbit coupling, and is given by [4]

$$\frac{1}{\tau_s} = \frac{16 k_B T (m^*)^3 (\gamma \Delta E_{1e})^2 \tau_p}{\hbar^8}, \quad (2)$$

where γ is a material-specific parameter related to the spin splitting of the conduction band and is proportional to the spin-orbit splitting, ΔE_{1e}, the electron confinement energy (ECE), m^* the electron effective mass, and τ_p the momentum relaxation time. Eq. (2) shows how the spin relaxation rate depends on the spin-orbit interaction (γ) and the electron confinement energy. The ECE value for the three structures calculated by SPECCODE is given in Table I, and the ECE for the $GaAs_{0.64}P_{0.36}$/GaAs structure is 49 meV. Sample 1 has a factor of 1.6 larger ECE than the reference strained-well $GaAs_{0.64}P_{0.36}$/GaAs structure. Comparing the two strained-barrier samples, Sample 2 has a factor of 2.5 larger ECE than Sample 3, resulting in a factor of 6 larger spin relaxation rate according to Eq. (2). In a superlattice structure with a larger ECE, the electrons will scatter more at the barriers, resulting in a spin depolarization and a lower vertical transport probability and therefore a lower QE. Furthermore, because of the scatterings the average photoemission time may be much longer than 3 ps, becoming more susceptible to spin depolarization. Aulenbacher et al. reported a significantly longer photoemission time for an InAlGaAs/AlGaAs superlattice structure, suggesting that the superlattice barrier layers are responsible [5].

CONCLUSIONS

In an attempt at reducing the spin relaxation in superlattice, InGaP/GaAs strained-superlattice structures were investigated. The photocathode performance is found dependent on the superlattice parameters. Especially the electron confinement energy appears very important.

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